Carbon nanotube addition to cement-sand based piezoelectric composites

Alec Kadlec, Shifa Wang, Ping Zhao
Department of Mechanical and Industrial Engineering
University of Minnesota: Duluth
Duluth, MN 55812 USA

Abstract:

Carbon Nanotubes (CNTs) were added to a cement-sand based piezoelectric composite with consideration of Structural Health Monitoring (SHM) to improve conductivity and poling efficiency, increasing piezoelectric effects. The addition of CNTs to the composite structure formed continuous electric networks between the Lead Zirconate Titanate (PZT) particles, allowing more effective poling. Samples of 50 volume percent PZT were fabricated with a mixture of PZT powder, white Portland cement, graded silica sand, CNTs and a superplasticizer, and cured at room temperature. The properties of the composite, including piezoelectric coefficient and sensing effects were characterized for a range of CNT inclusion from 0 to 0.9 vol %. Results showed that CNT inclusion allowed for effective room temperature poling, improving piezoelectric properties of the composite. The modified composite was optimal at 0.6 vol % CNTs.

Keywords: Piezoelectric composite, cement, carbon nanotubes, lead zirconate titanate, structural health monitoring

Introduction:

Cement-based piezoelectric smart composites have been studied with consideration of their applications for structural health monitoring (SHM) of concrete civil structures.[1-3] Embedded sensors would prove effective as a non-invasive, non-destructive method for monitoring loading and health of civil structures over their life. Such smart composites of PZT powder dispersed within a cement matrix allowed for better signal transfer than pure piezoceramic sensors. Further study proved sand inclusion in such composites was feasible and important for comparable strength properties and compatibility.[2, 3] In piezoelectric materials, their characteristic properties and performance capabilities are determined by poling conditions.[4] Difficulties with poling PZT-cement composites has been shown due to the greater electrical impedance of cement, necessitating increased temperature or applied electric field, but both of these conditions may negatively affect the strength of the cement due to crack growth and increased porosity under such high temperature.[5] In order to facilitate effective poling at low electric field and room temperature, conductive fillers were introduced into the composite, such as carbon black or CNTs. These proved to increase electrical conductivity of the composite and improve poling by greater electrical field available to the PZT ceramic phase.[6] Thus, conductive carbon fillers were shown to improve poling and enhance piezoelectric properties.

Much prior study has focused on cement-based piezoelectric composites and compatibility needs for practical applications, but utilized fabrication methods that may have been dissimilar to practical concrete production methods. While some applications apply pressure or heat to concrete during curing, this is not the most common method, where reinforced concrete is left to cure at room temperature and pressure. Thus, normal mixing of cement-sand PZT composites was used attain a compatible composite with desirable piezoelectric properties. To improve poling issues faced due to the cement matrix, CNTs were incorporated to the composite and studied. Additionally, a superplasticizer was included to facilitate effective dispersion of said CNTs, which otherwise tend to clump.[7] Piezoelectric coefficient and sensing effect of the cement-sand PZT composite with CNT inclusion were measured. This developed composite is more suitable for practical SHM application in concrete structures.

Experimental Procedure:

Cement-sand PZT composite samples were prepared by mixing PZT ceramic powder, white Portland cement, graded silica sand, CNTs and a superplasticizer. The density values of the components are listed in Table 1. The PZT powder, cement and sand were first mixed in an acetone at room temperature until the acetone evaporated to ensure uniform mixture. Then the CNTs, superplasticizer and water were added and stirred to uniform slurry. The composite consisted of 50 vol % PZT, and CNT composition ranging from 0 to 0.9 vol % in 0.1 vol % increments. The slurry was placed in molds of 15mm x 15mm area and a thickness of approximately 5 mm. These samples cured for 1 week at room temperature with no added pressure. After drying and processing of the samples to ensure even thickness, a silver epoxy was applied to serve as electrodes for the poling process. The specimen was poled under a DC electric field of 1 MV/m for 30 min at room temperature while submerged in a silicon oil bath to prevent sparking.

Table 1: Component density values

Component	Density $\boldsymbol{\rho}$
PZT powder	7.7×10^3 kg/m^3
White Portland cement	3.15×10^3 kg/m^3
Silica sand	1.6 X 10^3 kg/m^3
CNT (True density)	2.1×10^3 kg/m^3

Piezoelectric coefficient (d_{33}) was measured using a d_{33} tester. Sensing characteristics were measured under cyclic compressive loading for a variety of stress levels ranging from 2 MPa to 12 MPa with concurrent voltage output measurement through a data acquisition system.

Results:

In this study, CNT inclusion in cement-sand PZT composites allowed for effective distribution of applied electric field across PZT particles to enhance poling efficiency and resultant piezoelectric properties.

<u>Piezoelectric Coefficient:</u>

Figure 1 shows the effect of CNT inclusion in the composite on piezoelectric coefficient d_{33} in the post poling values. All samples had a similar pre-poling d_{33} value of approximately 0.7 pC/N. Post poling values of d_{33} increased with increasing CNT inclusion from 0 to 0.6 vol %. At 0.6 vol % the highest average d_{33} value of 13.0 pC/N is achieved, 4.8 times greater than the d_{33} value of the composite without CNT inclusion. The CNTs allow a continuous conductive matrix between the PZT particles, represented in Figure 2, which is otherwise unavailable without CNT inclusion. This improves poling effectiveness of the composite, resulting in the increasing d_{33} values. However, after increasing CNT inclusion past 0.6 vol %, the post-poling d_{33} values decrease, explained by the percolation behavior of the composite achieved at low conductive filler concentration. After exceeding percolation threshold, the conductive phase, CNTs, are in full contact within the matrix, allowing good electrical conductivity. This leads to short circuits within the specimen during poling, breaking down the composite.[8]

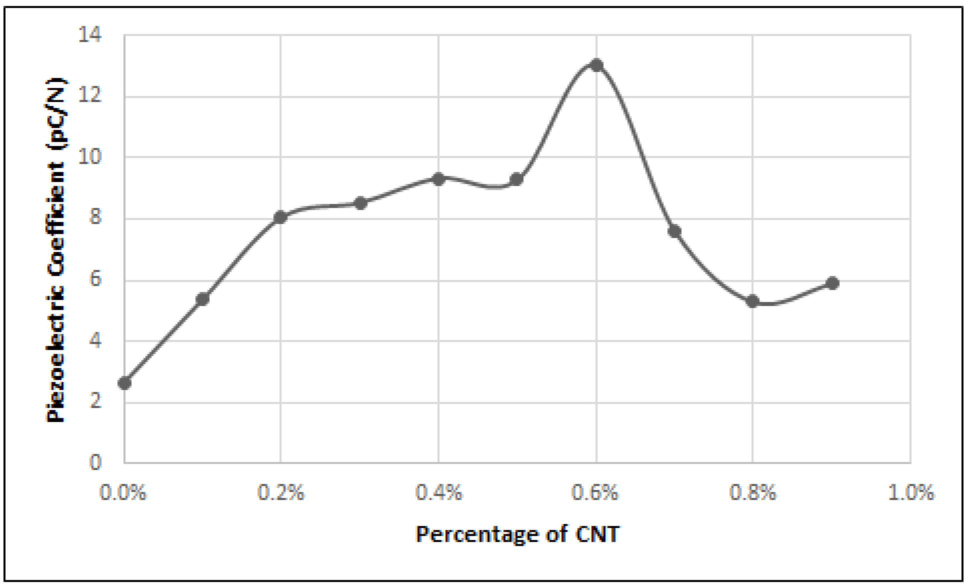

Figure 1: Effect of CNTs on piezoelectric coefficient d_{33}

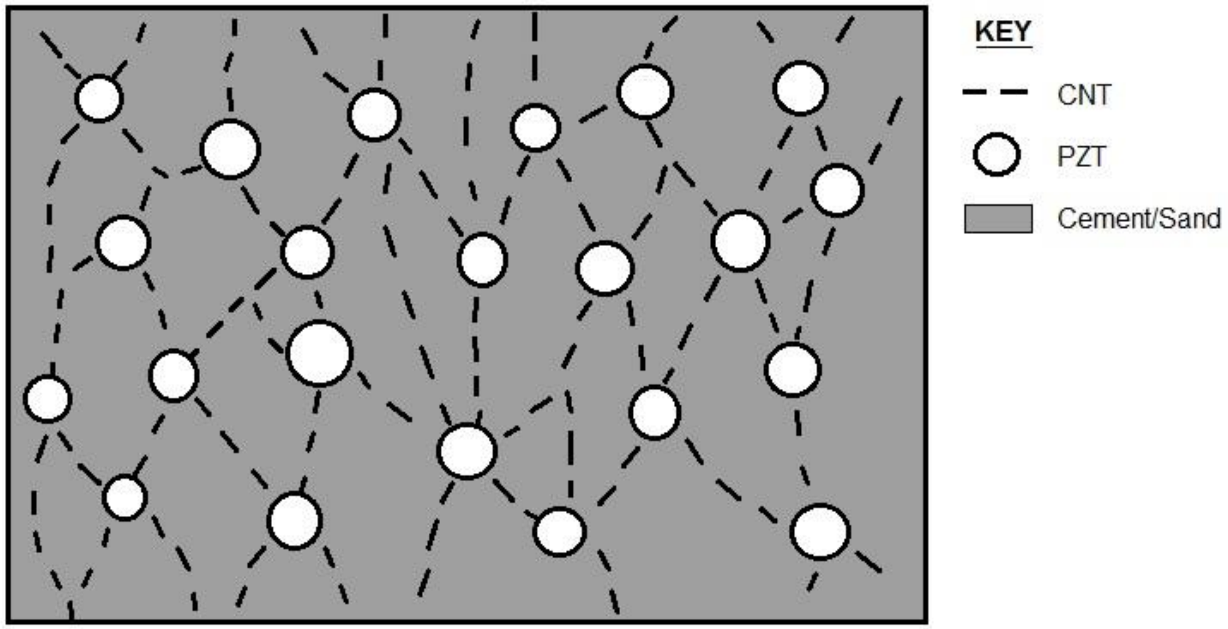

Figure 2: Diagram of conductive matrix

<u>Sensing Effect:</u>

Compression tests were undergone to characterize the sensing effect of the composites. These tests were done at a low frequency of 0.2 Hz, a value within the expected structural vibration range in civil engineering of 0-4.0 Hz due to wind or tectonic action.[9] The applied compressive loading cycle was a 0.2 Hz sinusoidal stress repeated for a different stresses ranging from 2-12 MPa, stress ranges slightly greater than those expected in civil structures.[9] Figure 3 shows the voltage (peak to peak value) output of the loading cycles of the 10 MPa applied stress, representing a similar response to those other applied stress values.

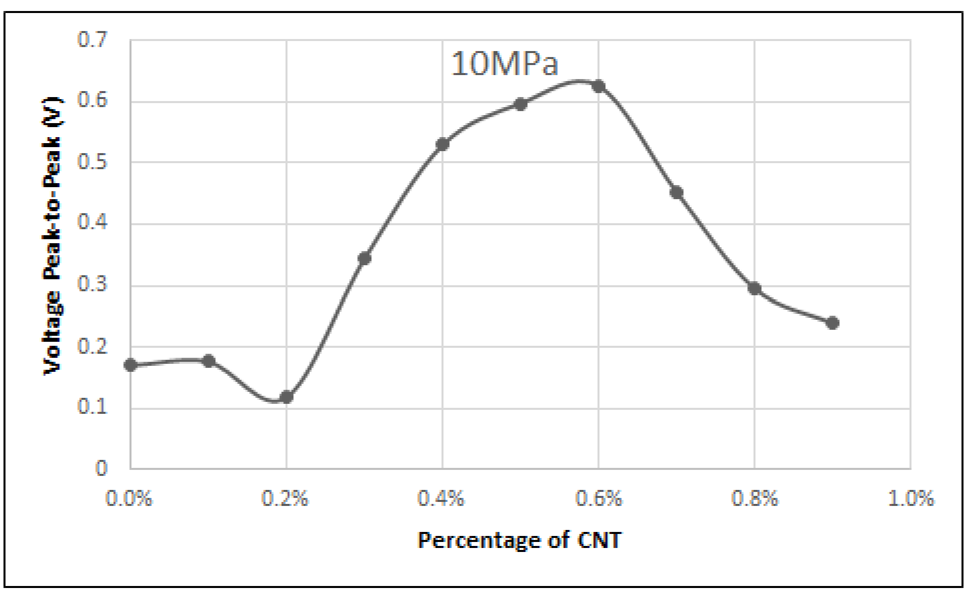

Figure 3: Voltage output under compressive loading - 10 MPa

As shown in Figure 3, 0.6 vol % inclusion of CNT resulted in the greatest voltage response of 0.63 V_{PP}. This is indicative of both a greater voltage response, showing improved effect of poling, and a greater range of values, allowing more effective use as a sensor within SHM by way of improving the effective sensing range. The results also showed that different stress values result in different voltage outputs, indicating the practical use of this composite for sensors in SHM applications.

Conclusions:

A cement-sand based piezoelectric composite was fabricated in line with practical methods for reinforced concrete. CNTs ranging from 0 to 0.9 vol % inclusion were added to a 50 vol % PZT matrix to improve conductivity and subsequent effect of poling. The effect of the extent of CNT inclusion was characterized through piezoelectric coefficient d_{33} testing and sensing effect characterization under compressive cyclic loading. The d_{33} values improved with increasing CNT inclusion up to 0.6 vol % CNTs, which exhibited a d_{33} of 13.0 pC/N, a more than fourfold increase over no CNT inclusion. Greater than 0.6 vol % CNT inclusion proved to reduce the d_{33} value, likely due to the percolation effect. The sensing effect also improved with increasing CNT content up to 0.6 vol % CNTs, after which it also decreased. These results indicate that CNT inclusion in such composites improves the effect of poling, resulting in more effective composites for SHM applications.

Funding:
This study was performed at the University of Minnesota Duluth with funding provided through the Undergraduate Research Opportunities Program (UROP).

References:

1. Kim, S., Zhao, P., & Enemuoh, E. (2015). Effect of carbon nanotubes on properties of cement-sand-based piezoelectric composites. *Behavior and Mechanics of Multifunctional Materials and Composites 2015, 9432*.
2. Zhao, P., Kim, S., Braden, J., et al. (2014) Properties of Cement-Sand Based Piezoelectric Composites. *Proceedings of the ASME 2014 Smart Materials, Adaptive Structures and Intelligent Systems.* Newport, RI, September, 2014
3. Zhao, P., Kim, S., & Hinderliter, B. (2015). Investigation of cement-sand-based piezoelectric composites. *Journal of Intelligent Material Systems and Structures*.
4. Mazur, K. (1995). *Ferroelectric Polymers*. NY: Marcel Dekker. Polymer-Ferroelectric Ceramic Composites
5. Janotka, I., & Nürnbergerová, T. (2005). Effect of temperature on structural quality of the cement paste and high-strength concrete with silica fume. *Nuclear Engineering and Design, 235*(17-19), 2019-2032
6. Huang, S., Li, X., Liu, F., et al. (2009). Effect of carbon black on properties of 0–3 piezoelectric ceramic/cement composites. *Current Applied Physics, 9*(6), 1191-1194

7. Han, B., Zhang, K., & Yu, X. et al. (2012). Fabrication of piezoresistive CNT/CNF cementitious composites with superplasticizer as dispersant. *Journal of Materials in Civil Engineering, 24*, 658-665.
8. Bauhofer, W., & Kovacs, J. Z. (2009). A review and analysis of electrical percolation in carbon nanotube polymer composites. *Composites Science and Technology, 69*(10), 1486-1498.
9. Dong, B., & Li, Z. (2005). Cement-based piezoelectric ceramic smart composites. *Composites Science and Technology, 65*(9), 1363-1371.